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PRELIMINARY AERODYNAMIC AND STRUCTURAL TESTS SHOWING THE EFFECT OF COMPRESSIVE LOAD ON THE FAIRNESS OF A LOW-DRAG WING SPECIMEN WITH CHORDWISE HAT-SECTION STIFFENERS

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ADVANCE CONFIDENTIAL REPORT

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SUMMARY

A cooperative investigation by the air-flow research and structures research sections of the National Advisory Committee for Aeronautics was made as part of a research program to obtain structures suitable for low-drag wings. The purpose of this particular investigation was to study the drag characteristics of an NACA 66(215)-(1.25)16 airfoil specimen of two-spar construction with hat-section chordwise stiffeners after a compressive load comparable with the maximum applied flight load of a modern military airplane has been applied and removed. The results of the aerodynamic and structural tests presented indicate that the drag characteristics of a wing employing this type of structure would probably not be changed after the wing has been subjected to its maximum applied flight load.

Although some structural tests had been previously made on a wing specimen with spanwise stiffeners, no confirmatory wind-tunnel tests were made on that specimen. It should be emphasized, therefore, that of the two types of construction so far studied there is not sufficient evidence at present to conclude whether the type of construction described in this report or the spanwise-stiffener type of construction previously tested is to be favored as regards low drag after the maximum flight load has been applied and removed.

INTRODUCTION

In a cooperative investigation made at LMAL by the air-flow research section and the structures research section, tests were conducted on a practical construction model of an NACA 66(215)-(1.25)16 airfoil section, which was constructed in the sheet-metal shop at LMAL. The model, as received from the shop except for the repair of slight local defects, was first tested in the two-dimensional low-turbulence pressure tunnel to determine the drag characteristics. The structures research section then tested the model by alternately applying and removing progressively larger compressive loads until some permanent deformation was noted in the skin. Upon removal of the compressive load, surveys to detect any change in fairness of the skin were made by rolling a straight edge (see reference 1) over the skin in a chordwise direction. When an additional flat spot, even of minor severity, was detected for the first time, drag tests of the model were again run in the two-dimensional tunnel. In this manner quantitative results could be obtained, because any drag increment due to increased unfairness in the model resulting from the loading could be shown.

MODEL

The NACA 6-series airfoil used, which was of $35\frac{3}{4}$-inch span and of 72-inch chord, was a wing panel of NACA 66(215)-(1.25)16 airfoil section. The specimen employed a two-spar construction with solid or full end ribs and with false nose and tail ribs, spaced at 6-inch intervals between the full end ribs, and with chordwise hat-section stiffeners, spaced at 6-inch intervals, supporting the skin between spars. The spars were located at 15 and 72.5 percent of the chord. The skin was attached with rivets driven by method B as described in reference 2. A drawing of the airfoil section is given in figure 1 and a photograph of the specimen is shown in figure 2.

AERODYNAMIC TESTS

Test Methods

The aerodynamic tests consisted of drag measurements made in the two-dimensional low-turbulence pressure tunnel by the wake-survey method, and the test procedure conformed with that outlined in reference 3.

The model was originally tested for drag characteristics in the condition in which it was received from the shops except for the glazing of the seams at the front spar with pyroxylin putty and the repairing of a few minor scratches on the airfoil surfaces by sanding or filling with glazing putty. This model condition will be referred to as the before-loading condition. The model was then subjected to loading tests in the structures research laboratory, after which a few local surface imperfections were repaired in an attempt to reproduce the detail surface condition before loading. These imperfections, which resulted from permanent set of several rivets, could probably have been avoided by a change in rivet spacing. Their repair is believed justified because the presence of such defects would have invalidated the results with respect to determining any drag increments resulting from increased unfairness of the model. Any flat spots on the surface, however, were left untouched. A second set of drag tests were made of the model in this condition, which will be referred to hereinafter as the after-loading condition.

Results and Discussion

The variation of section drag coefficient with Reynolds number for the wing specimen model of an NACA 66(215)-(1.25)16 airfoil is shown in figure 3 for the before-loading and the after-loading conditions; for comparison, the results of a previously tested, camouflage-painted, practical-construction model of an intermediate wing section, an approximate NACA 66(2 × 15)-116, a = 0.6 airfoil, also are given. From a comparison of the drag curves presented, it appears that the drag values as shown for the NACA 66(215)-(1.25)16 airfoil could be lowered because it is probable that surface conditions could have been improved to obtain results comparable with those of the approximate NACA 66(2 × 15)-116, a = 0.6 airfoil. The drag increments obtained for the before-loading and after-loading conditions give an indication of the change in model fairness.

The variation of section drag coefficient with section lift coefficient at several values of the Reynolds number for the section tested is given in figure 4 for the before-loading and after-loading conditions. Because of the inaccuracies in results (due to stream constriction) that arise in the two-dimensional low-turbulence pressure tunnel with large-chord models at high angles of attack, tests were made through only a small angle-of-attack range.

Figures 3 and 4 show that the drag coefficients at Reynolds numbers up to 24,000,000 are approximately the same for the two model conditions although, at Reynolds numbers greater than 24,000,000, the drag of the model for the after-loading condition is lower than that for the before-loading condition despite the fact that every effort was made to keep local surface details the same for both loading conditions. This decrease in drag, which may be attributed to an accidentally smoother finish for the after-loading condition caused by refinishing the model after the compression tests, indicates the order of accuracy of the tests. It is believed that any drag increases resulting from a significant unfairness in the model would be of such magnitude that they would not be masked by the drag decreases resulting from the accidentally smoother surface finish. The slight additional unfairness in the model that resulted from the compressive loading to which the model was subjected appears to have no adverse effects on the drag characteristics of the model as shown by a comparison of the before-loading and after-loading conditions. It is not known what would have been the effect of this slight additional unfairness on the drag characteristics if the surface conditions of the wing-specimen model had been as good for the before-loading test as the surface conditions for the approximate NACA 66(2 × 15)-116, a = 0.6 airfoil. (See fig. 3.)

STRUCTURAL TESTS

Test Methods

After the airfoil was tested in the two-dimensional tunnel where its drag characteristics were determined, it was placed in the 1,200,000-pound-capacity testing machine in the structures research laboratory, where two types of compressive tests were made. In the first type of test the model was subjected to compression with uniform bearing on both ends and a varying internal pressure was applied to the airfoil in order to determine the effect that a reduced pressure over the outside surface might have on the size of buckles that might form in the wing surface when an airplane is in flight. In the second type of test, the load on the specimen was applied through two spars at one end of the specimen while the other end was in uniform bearing.

Strain measurements were taken during the course of the tests to determine the probable stress distribution in the airfoil for a given applied load. The airfoil fairness was determined by the method used and explained in reference 1.

Results of Tests with Uniform Bearing on Cross Section

Structural action.- Figure 5 shows that the curve of observed average spar strain plotted against applied load is approximately linear up to loads in the vicinity of 40,000 pounds, at which definite buckles were observed in the skin. At loads above 40,000 pounds, the slope of the curve decreases with an increase of load, which indicates that the skin was losing its effectiveness in resisting higher loads.

Figure 6 shows the relation between the applied load and the area that was effective in resisting this load. The effective area was determined by dividing the load by the absolute stress in the spars. This stress was obtained by converting the strains of figure 5 into stresses, a modulus of elasticity of 10.7×10^6 pounds per square inch being used. Figure 6 also presents a curve showing the efficiency of the cross section plotted against load. This efficiency is computed as the ratio of the average stress over the cross section to the stress in the spars; it may also be considered the ratio of the effective area to the total area of the cross section.

The average stress at which buckles were first noticed in the skin was 3100 pounds per square inch. These buckles developed into the form of waves along the specimen and extended over almost the entire distance between the spar caps. A photograph of the airfoil under a load of 85,000 pounds is shown in figure 7, in which the wave form or buckle pattern of the skin is revealed by the reflection of a straightedge placed along the spanwise direction of the airfoil. Figure 8 shows the observed variation between depth of a typical buckle and applied internal air pressure to simulate reduced pressures outside the airfoil, with the specimen under a load of 85,000 pounds; at a pressure difference of 1.4 pounds per square inch, the depth of the buckles becomes quite small.

Under a total load of 131,800 pounds, a local buckling failure was observed in the trailing edge of the specimen and consequently no additional load was applied for fear of completely destroying the trailing-edge skin panels. A photograph of this local failure is shown in figure 9, which also shows the severe buckling pattern that was develcped in the skin along the spar caps.

Fairness surveys.- The results of all the fairness surveys are shown in figure 10. The initial survey indicated that the airfoil had several flat areas of minor severity before loading. For loads up to a total load of 90,000 pounds the chordwise fairness surveys, as made by rolling a straightedge over the surface, indicated only a small increase in the number of flat spots, even though the skin had a very pronounced wave pattern along its spanwise direction. At loads greater than 90,000 pounds the airfoil could definitely be regarded as not fair, because numerous buckles occurred in the nose and tail portions and especially in the region along the spar-cap flanges. Although there were severe buckles in the skin at high loads, the fairness surveys showed no evidence of any permanent deformation in the surface of the airfoil even after the maximum load of 131,800 pounds had been applied and removed.

Results of Tests with Load Applied through Spars at One End of the Wing Specimen

Structural action.- When the model was tested with both end cross sections bearing, the stress developed could not be brought up to the desired value because of the possibility that the model would become permanently damaged; another test was therefore conducted in which the load was applied through the two spars at one end of the specimen. A photograph of the airfoil in the testing machine under this test condition is shown in figure 11.

A curve of average strains in the spar caps at the points of application of the concentrated loads plotted against the total applied load is shown in figure 12. For comparison, a theoretical curve derived on the assumption that only the area under the loading blocks resisted load is also presented. This area was equal to 4.98 square inches and was taken as the area of the spar caps plus the effective area of the skin, which in this case was assumed to extend 20 skin thicknesses on either side of the spar caps. The general agreement between these two curves indicates that the computed effective area is of the correct order of magnitude. In figure 12, the curve of average strain along the airfoil, as determined from the over-all shortening measured with dial gages, is also plotted against applied load. At a given load these strains are somewhat smaller than the spar strains because the load tends to become more uniformly distributed throughout the airfoil as the distance from the concentrated loads increases.

At a total load of 175,000 pounds, which corresponds to an average stress of 35,200 pounds per square inch in the spar caps at the points of application of load, local failures developed in the skin adjacent to the loading blocks at the ends of the spars. The skin had permanent buckles between rivets, and there were indications that buckles had produced permanent rivet set in tension because several rivet heads were left protruding a few thousandths of an inch above the surface of the skin after the load had been removed. A photograph of a local failure is given in figure 13.

Fairness surveys.- The results of the fairness surveys for this type of test are shown in figure 14. For loads up to 82,000 pounds, the number of flat spots slightly increased with load; at this load, shear buckles began to occur in the region of the loading blocks. At higher loads, the extent and severity of these buckles became more and more pronounced and numerous buckles appeared along and adjacent to the spar cap flanges. No change in fairness from the original contour of the specimen was evident with successive application and removal of higher and higher loads until a load of 175,000 pounds was reached. On the removal of this load, several very small additional flat areas were found, as shown on the last sketch of figure 14. The corresponding average spar stress at which slight permanent deformation of the skin was first noted was 35,200 pounds per square inch.

Analysis of Results

If an airplane wing were constructed with the same type of construction that was used in the airfoil specimen, the ultimate stress that could be developed by the structure would be that of the material of the spar. If the design ultimate stress is taken as 60,000 pounds per square inch, the maximum stress that would be expected to be developed in the life of the airplane is two-thirds of this value, or 40,000 pounds per square inch. This value is slightly higher than the value of the stress at which some permanent set in the skin was found. It is possible that a higher stress than the value of 35,200 pounds per square inch developed in the test could have been attained without seriously affecting the fairness of the wing under no load. Under the assumption that only the spar caps are effective in resisting load and with a design load factor taken as 12, the compressive stress in level flight would be 60000/12 or 5000 pounds per square inch. This value is well below the stress in the spars at which buckling of the skin occurred when the specimen was loaded through the spars. This condition of loading would be similar to that of a wing having a cut-out in the upper surface. In the case of the test of the specimen in uniform bearing, however, the spar stress at which buckling occurred was only 3150 pounds per square inch and on first thought it would appear to be an unsatisfactory structure in level flight. Actually under level flight, the skin would take its full share of the load, and the spar stress would be reduced by the ratio of the area of the spars to the area of the spars plus the area of skin effective in bending. For the wing specimen, this ratio is about 1/2.2, which would reduce the spar stress from 5000 to 2270 pounds per square inch, a value below the critical buckling stress. The possibility of buckles forming is further alleviated by the presence of a negative pressure on the upper surface of the wing.

DISCUSSION OF CHORDWISE AND SPANWISE STIFFENING AS REGARDS WING FAIRNESS AFTER LOADING

The tests reported in reference 1 suggested a procedure for determining in advance the probable success of a particular type of construction for a low-drag wing when subjected to load. The results obtained, however, did not permit final conclusions to be made as to the suitability of skin with spanwise stiffeners for low-drag wings, because of the absence of confirmatory wind-tunnel tests.

The results of the aerodynamic and structural tests presented in this report indicate that the drag characteristics of a wing employing a structure consisting of two spars with hat-section chordwise stiffeners, as described herein, would probably not be changed after the maximum flight load had been applied and removed. The slight additional unfairness of the model resulting from the compressive loading to which it was subjected appears to have had no adverse effect on its drag characteristics.

It should be emphasized, however, that of the two types of construction so far studied there is not sufficient evidence at present to conclude whether the type of construction described herein or the spanwise-stiffener type of construction described in reference 1 is to be favored as regards low drag after the maximum flight load has been applied and removed.

CONCLUSIONS

The results of the aerodynamic and structural tests presented in this report indicate that the drag characteristics of a wing employing a structure consisting of two spars with hat-section chordwise stiffeners, as described herein, would probably not be changed after the maximum flight load had been applied and removed. The slight additional unfairness of the model resulting from the compressive loading to which it was subjected appears to have had no adverse effect on its drag characteristics.

Although some structural tests have been made previously on a wing specimen with spanwise stiffeners, no confirmatory wind-tunnel tests were made on the specimen. It should be emphasized, therefore, that of the two types of construction so far studied there is not sufficient evidence at present to conclude whether the type of construction described in this report or the spanwise-stiffener type of construction previously tested is to be favored as regards low drag after the maximum flight load has been applied and removed.

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2. Lundquist, Eugene E., and Gottlieb, Robert: A Study of the Tightness and Flushness of Machine-Countersunk Rivets for Aircraft. NACA RB, June 1942.

3. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Preliminary Low-Drag-Airfoil and Flap Data from Tests at Large Reynolds Numbers and Low-Turbulence. NACA ACR, March 1942.

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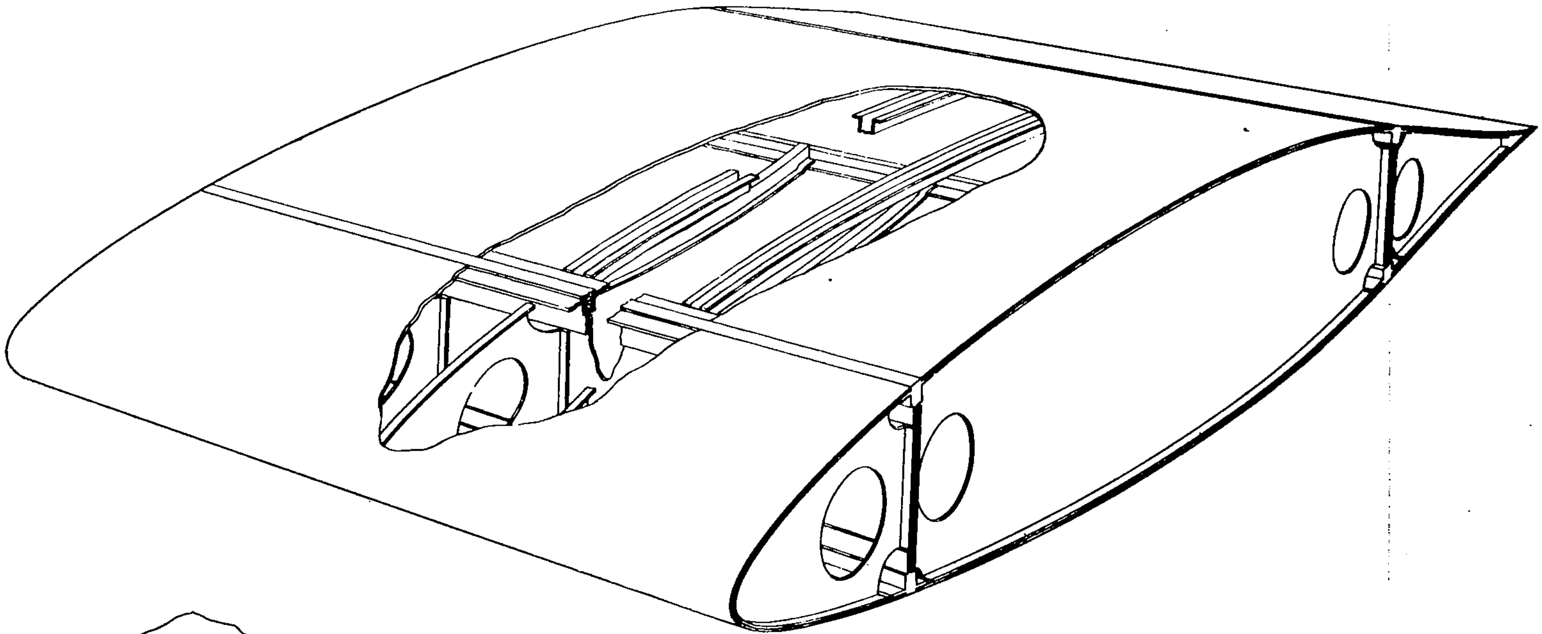
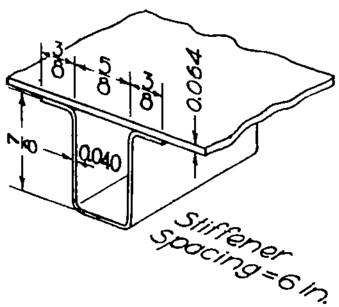




Detail of stiffener

FIGURE 1.—TWO-SPAR LOW-DRAG WING SPECIMEN WITH CHORDWISE HAT-SECTION STIFFENERS. 72-in chord.

Fig. 1

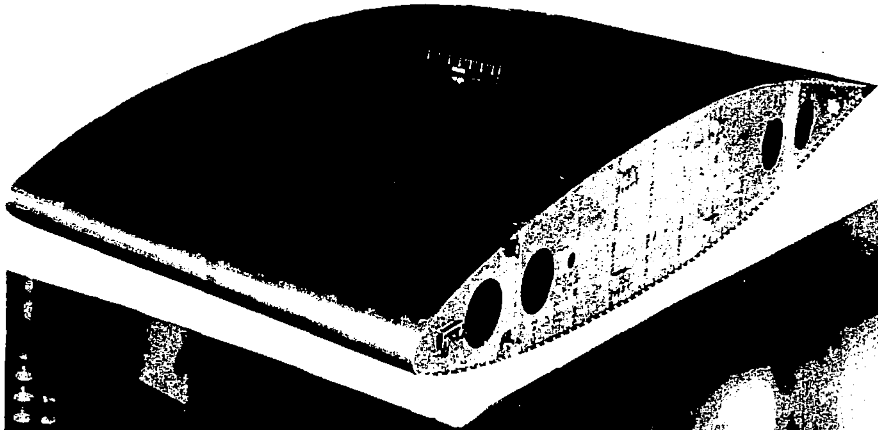


Figure 2.- Two spar low-drag wing specimen with chordwise stiffeners.

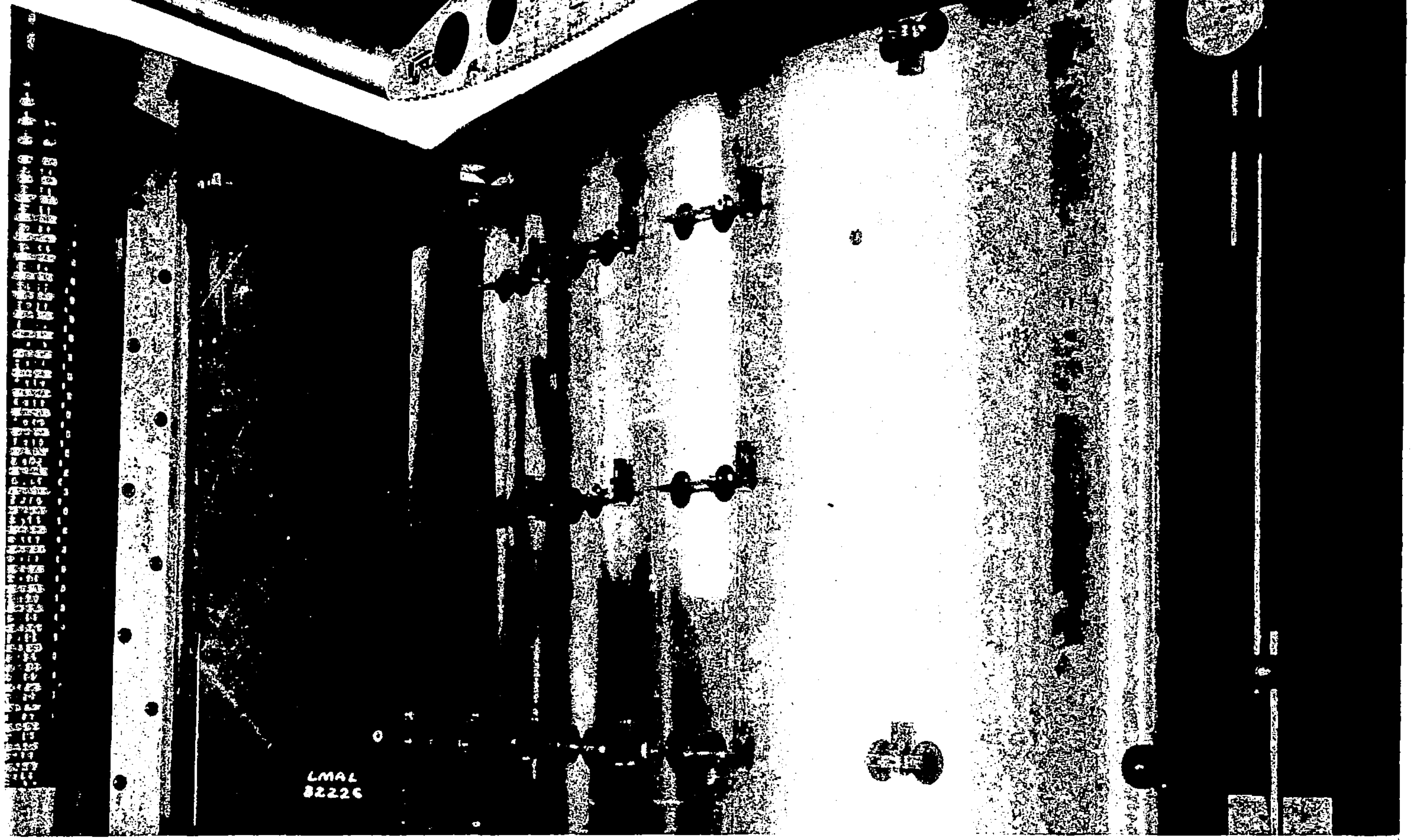


Figure 11.- Test of low-drag wing specimen with load applied through spars.

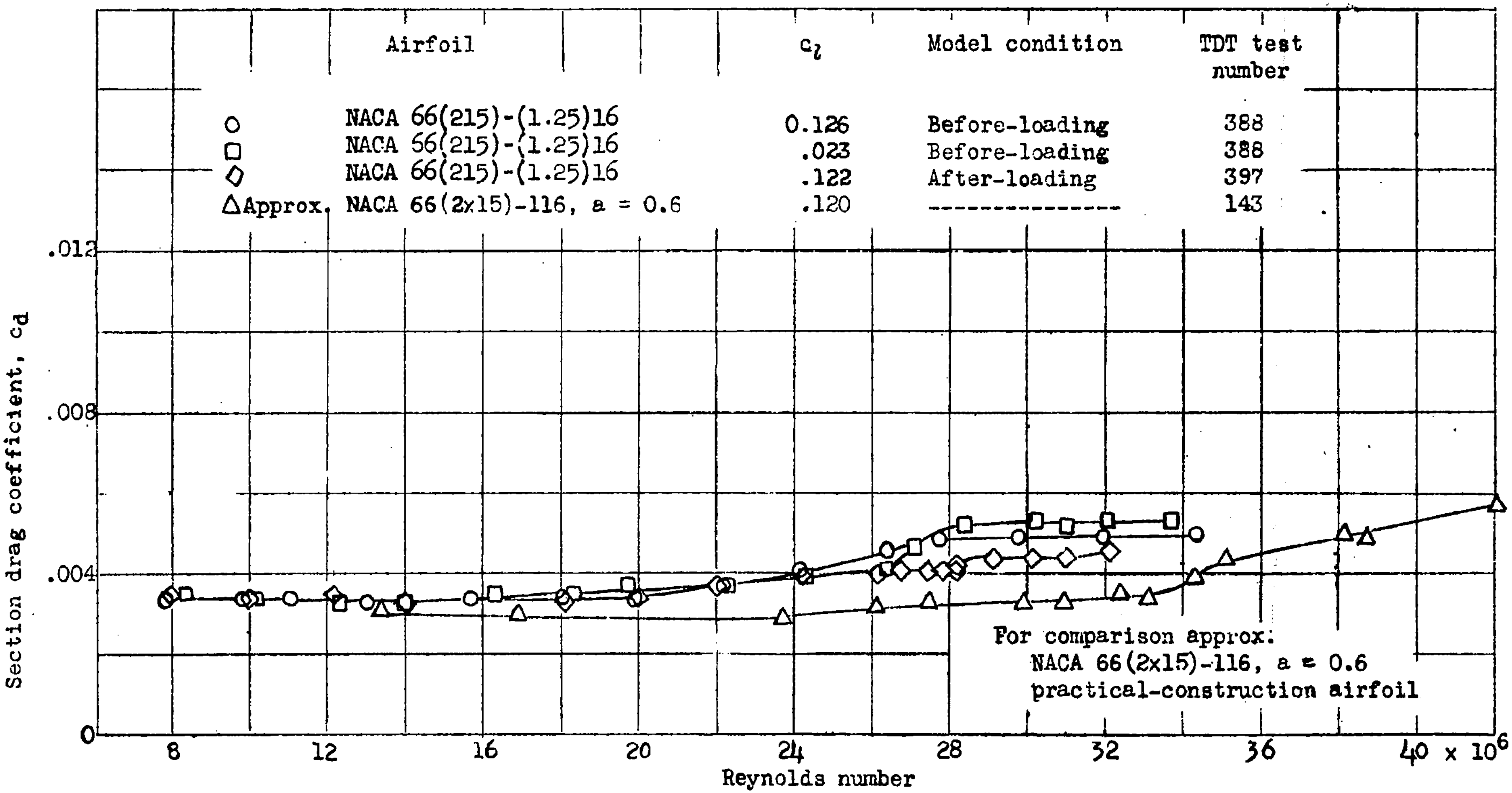
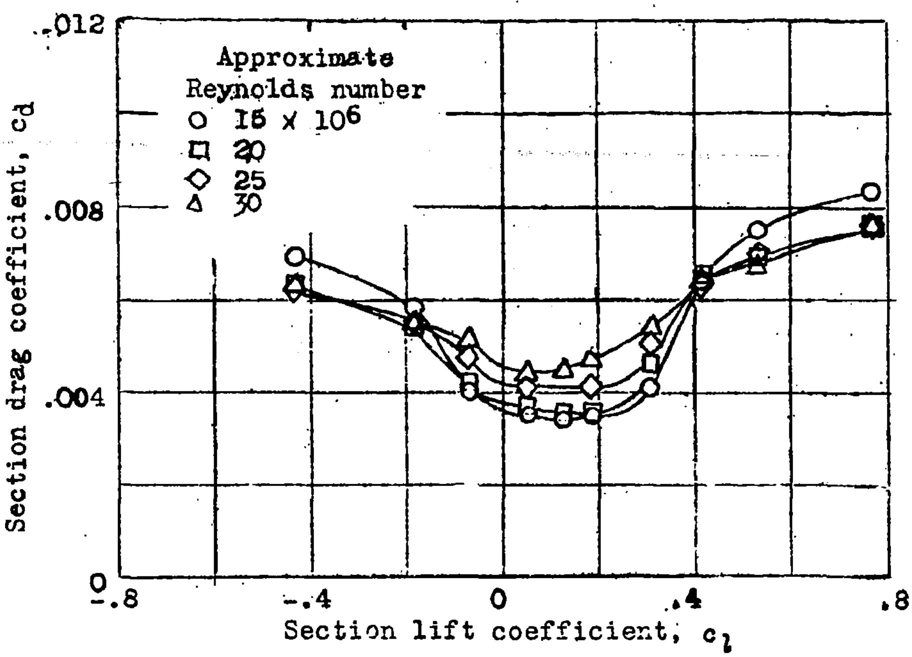
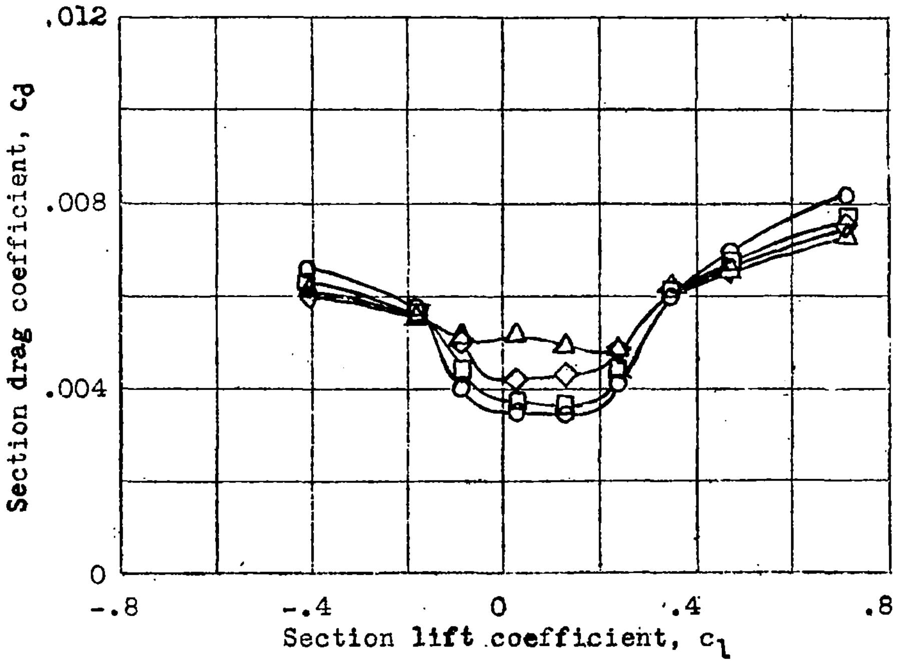


Figure 3.- Variation of section drag coefficient c_d with Reynolds number for an NACA 66(215)-(1.25)16 airfoil for before-loading and after-loading conditions.



After-loading condition



Before-loading condition

Figure 4.- Variation of section drag coefficient c_d with section lift coefficient c_l at several values of the Reynolds number for an NACA 66(215)-(1.25)16 airfoil for before-loading and after-loading conditions.

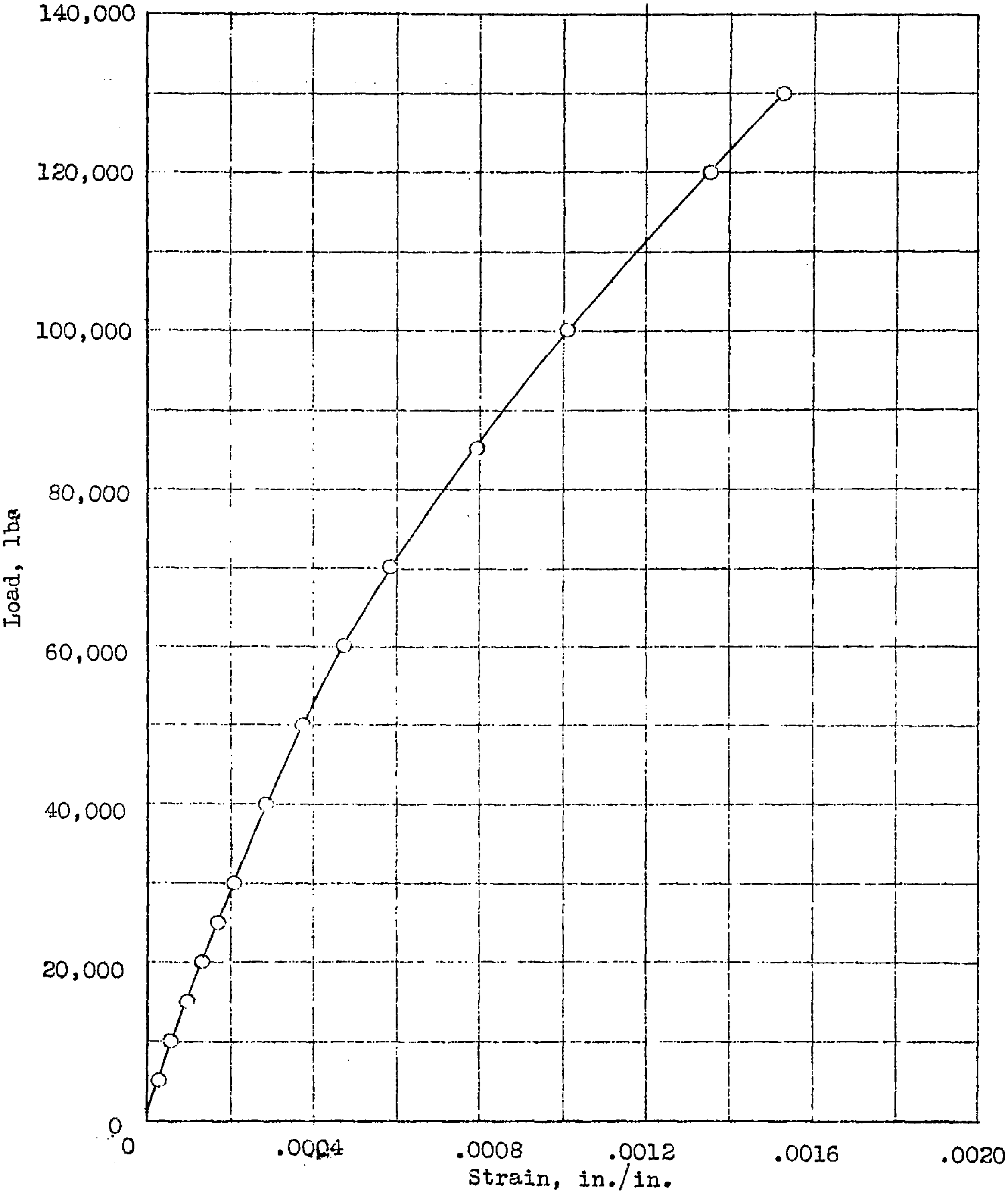


Figure 5.- Average strain in spars for test with uniform bearing on cross section of specimen.

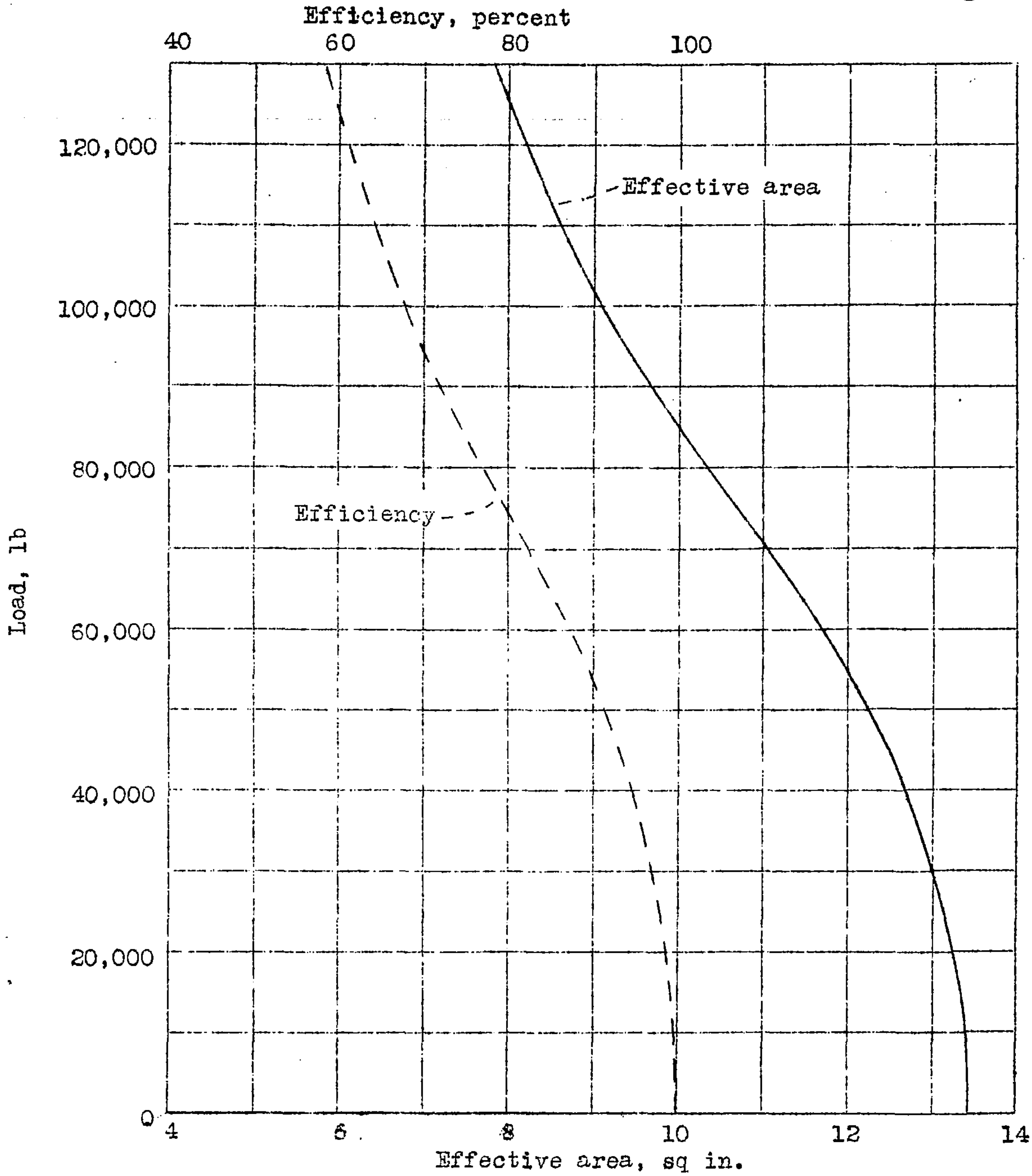


Figure 6.- Variation of effective area and efficiency of section with load.

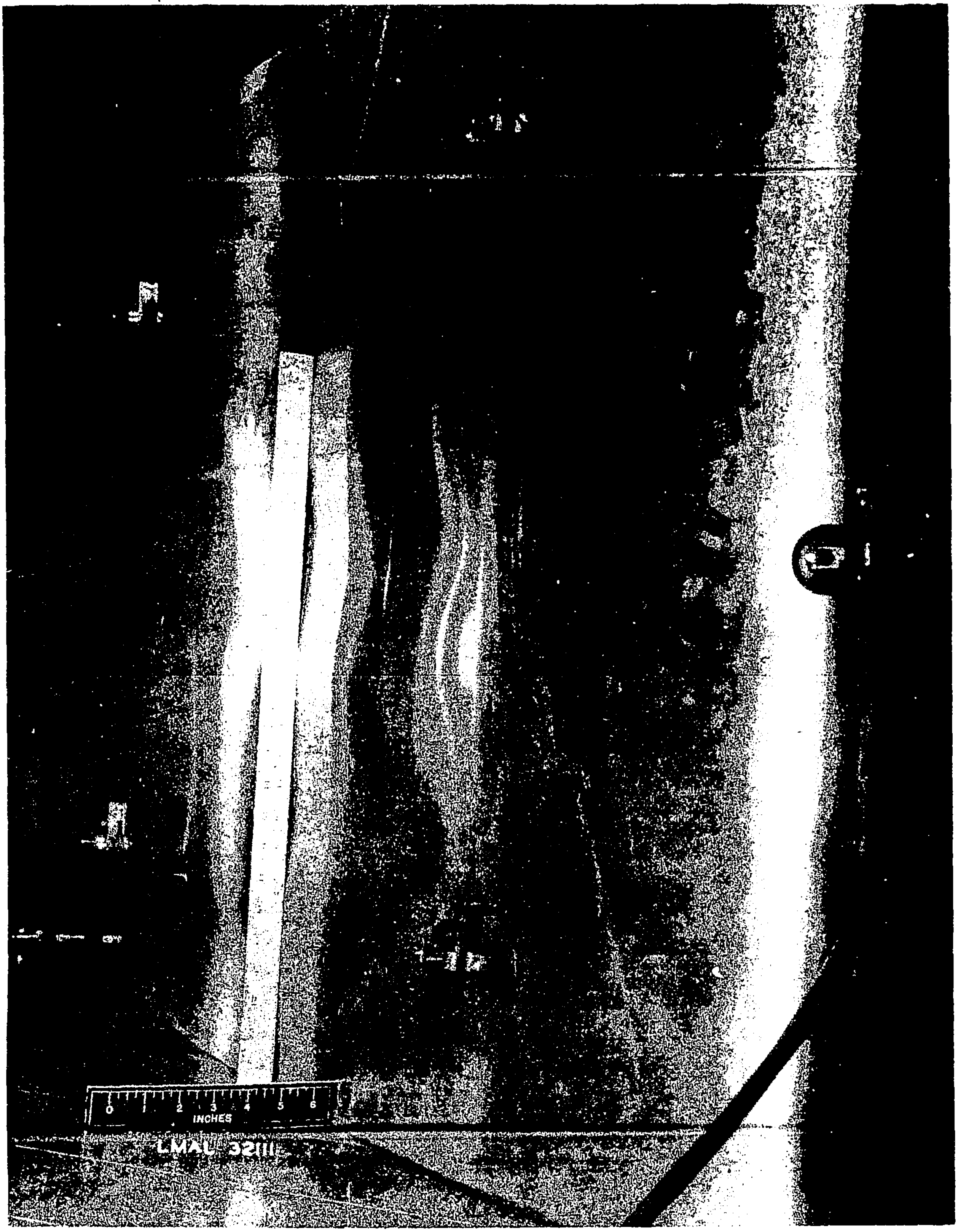


Figure 7.- Buckles in low-drag wing specimen at load of 85,000 pounds.

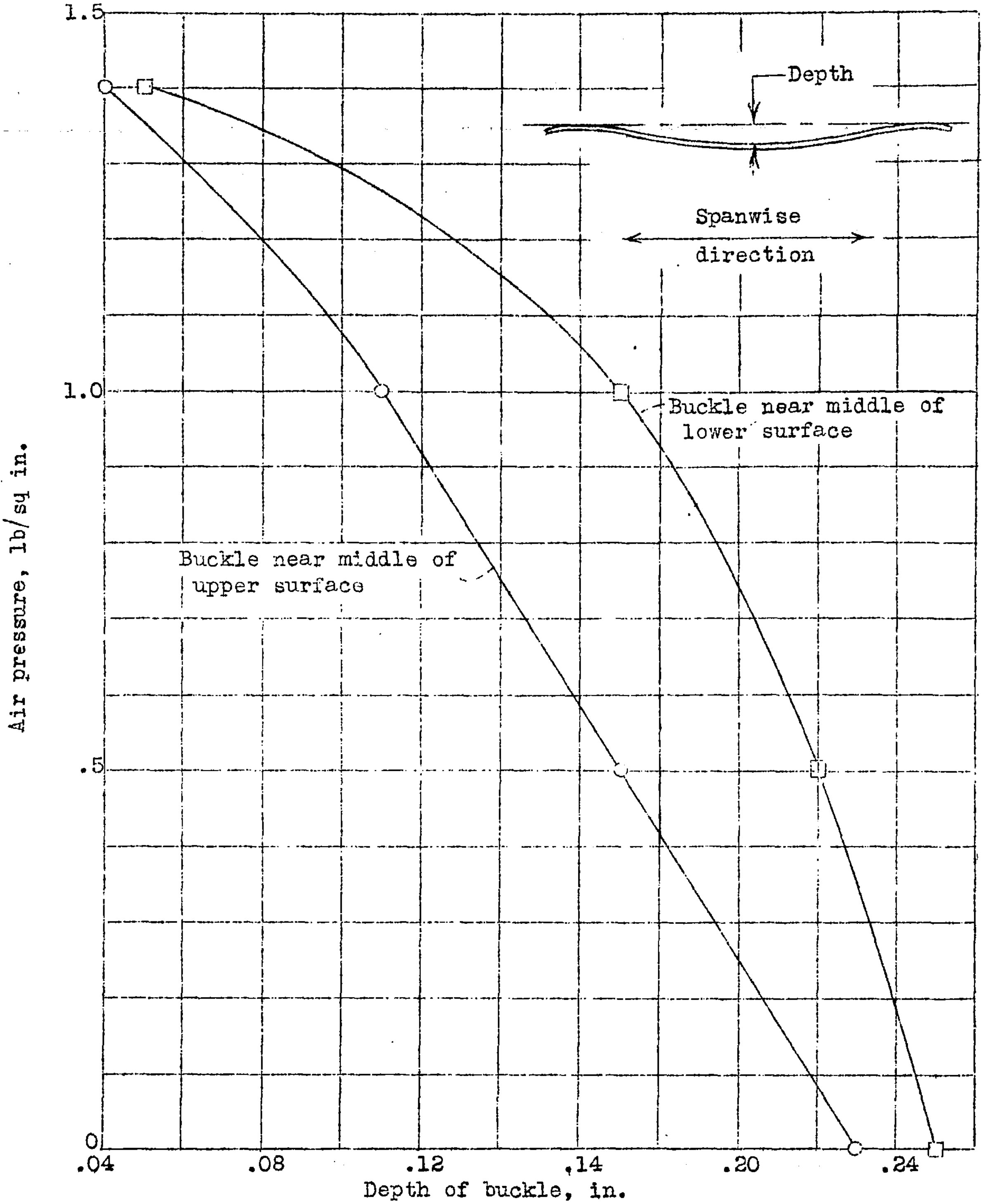


Figure 8.- Effect of normal pressure on depth of typical buckle. Total load on specimen, 85,000 pounds.

Figure 9.- Local failure of trailing edge of wing specimen.

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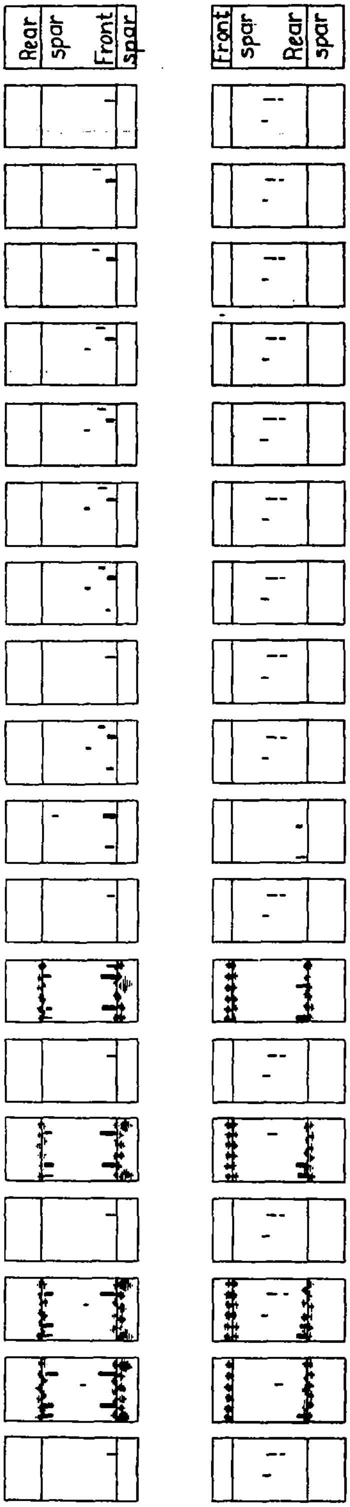
Fig. 10

Upper surface | Lower surface



Load history

Load, lb		Spar stress lb/sq in.
1,000		—
10,000		750
20,000		1,500
30,000		2,300
40,000	Definite buckles present	3,100
50,000		4,100
60,000		5,100
1,000		—
70,000		6,300
85,000		8,500
1,000		—
100,000	Numerous buckles along spars	11,000
1,000		—
110,000		12,700
1,000		—
120,000		14,600
130,000		16,600
1,000		—

Figure 10.- Fairness surveys on low-drag airfoil in uniform end compression. Weight and length of lines indicate severity and extent of flat spots.

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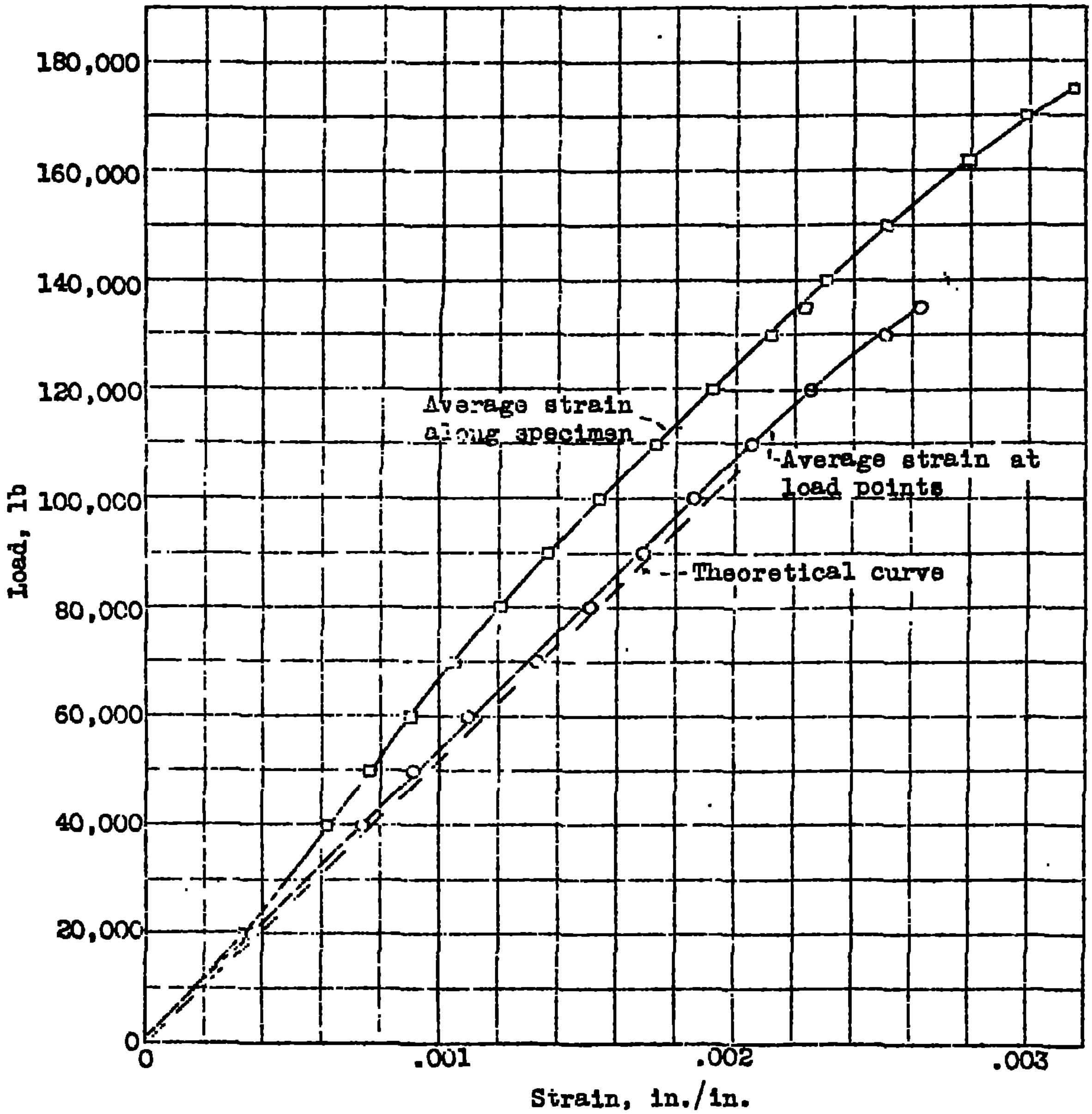

Figure 12.- Average strains in spars for test with load applied through spars.

Figure 13.- Local failure of skin near concentrated load.

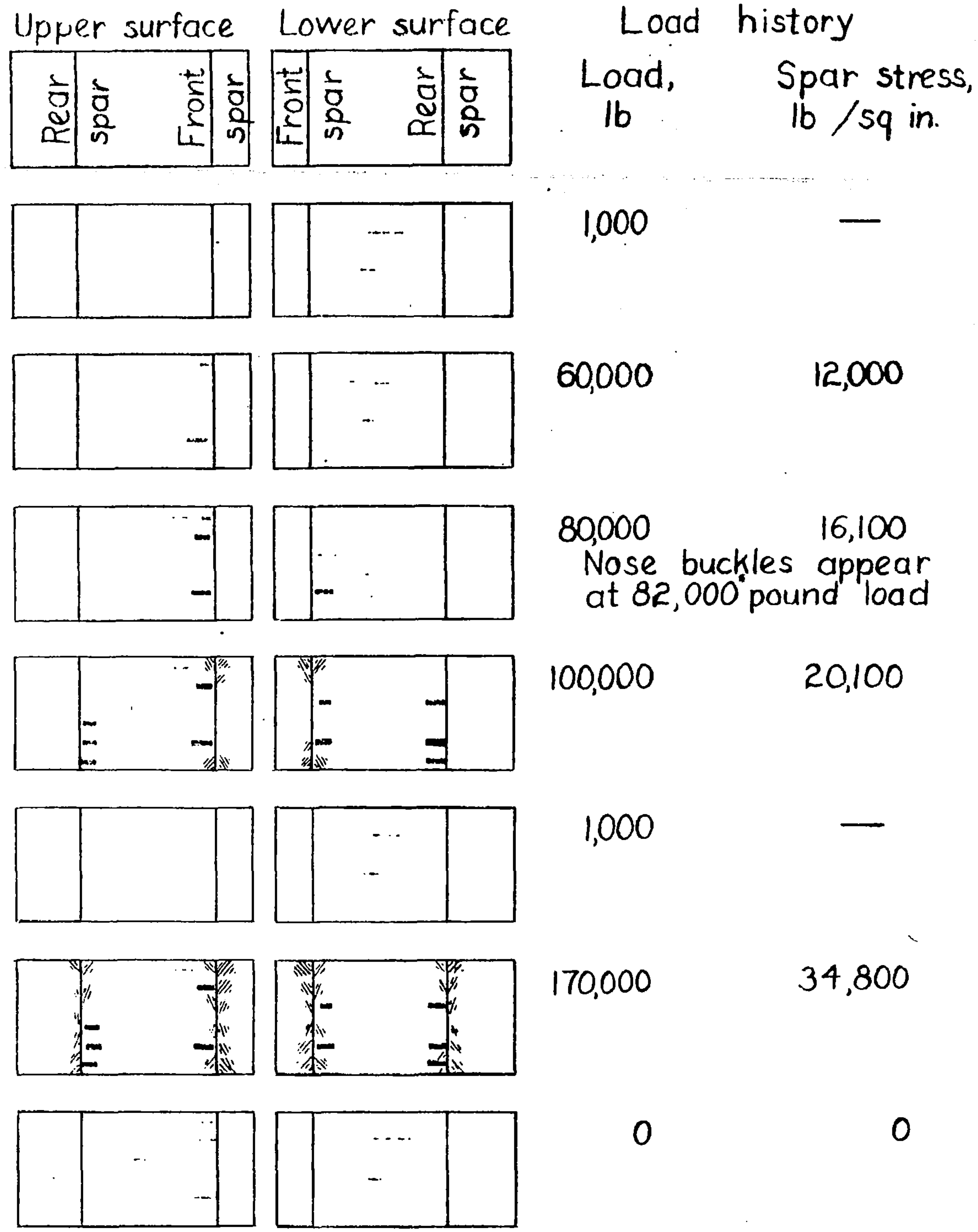

Figure 14.- Fairness surveys on low-drag airfoil in end compression with load applied through the spars.
Weight and length of lines indicate severity and extent of flat spots.